Frontiers in Earth Sciences

1

Victor A. Melezhik *Editor-in-Chief*
Anthony R. Prave · Eero J. Hanski
Anthony E. Fallick · Aivo Lepland
Lee R. Kump · Harald Strauss *Editors*

Reading the Archive of Earth's Oxygenation

Volume 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia – Drilling Early Earth Project

Springer

Frontiers in Earth Sciences

Series Editors: J.P. Brun, O. Oncken, H. Weissert, W.-C. Dullo

Victor A. Melezhik *Editor-in-Chief*
Anthony R. Prave
Eero J. Hanski
Anthony E. Fallick
Aivo Lepland
Lee R. Kump
Harald Strauss *Editors*

Reading the Archive of Earth's Oxygenation

Volume 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia - Drilling Early Earth Project

Springer

Editor-in-Chief
Victor A. Melezhik
Geological Survey of Norway,
Trondheim

Centre of Excellence in Geobiology
University of Bergen
Norway

Editors
Anthony R. Prave
Department of Earth Science
University of St Andrews
United Kingdom

Aivo Lepland
Geological Survey of Norway
Trondheim
Norway

Eero J. Hanski
Department of Geosciences
University of Oulu
Oulu
Finland

Lee R. Kump
Department of Geosciences
Pennsylvania State University
Pennsylvania
USA

Anthony E. Fallick
Environmental Research Centre
Scottish Universities
East Kilbride
United Kingdom

Harald Strauss
Institut für Geologie
Westfälische Wilhelms-Univ. Münster
Münster
Germany

ISSN 1863-4621
ISBN 978-3-642-29681-9 ISBN 978-3-642-29682-6 (eBook)
DOI:10.1007/978-3-642-29682-6
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012944339

© Springer-Verlag Berlin Heidelberg 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Dedication

The editors respectfully dedicate this three-volume treatise to Dr. Alexander Predovsky of the Geological Institute of the Russian Academy of Sciences in Apatity. He is one of the earliest explorers of the Precambrian geology in Russian Fennoscandia, and his half century of active work on the geochemistry of sedimentary and igneous rocks provided important foundations for the current understanding of Palaeoproterozoic stratigraphy, geochemistry of sedimentary and volcanic processes and ore formation in the region.

Contributors to Three-Volume Treatise Reading the Archive of Earth's Oxygenation, Volume 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia - Drilling Early Earth Project

Anthony E. Fallick Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride, Glasgow G75 0QF, Scotland, UK

Eero J. Hanski Department of Geosciences, University of Oulu, P.O. Box 3000, 90014 Oulu, Finland

Lee R. Kump Department of Geosciences, Pennsylvanian State University, 503 Deike Building, University Park, PA 16870, USA

Pavel V. Medvedev Institute of Geology, Karelian Research Centre, Russian Academy of Sciences, Pushkinskaya 11, 185910 Petrozavodsk, Russia

Victor A. Melezhik Geological Survey of Norway, Postboks 6315 Sluppen, NO-7491 Trondheim, Norway/Centre for Geobiology, University of Bergen, Allegaten 41, Bergen N-5007, Norway

Anthony R. Prave Department of Earth Science, University of St. Andrews, St Andrews KY16 9AL, Scotland, UK

Sergey A. Svetov Institute of Geology, Karelian Research Centre, Russian Academy of Sciences, Pushkinskaya 11, 185910 Petrozavodsk, Russia

Reviewers for Three-Volume Treatise: Reading the Archive of Earth's Oxygenation

Prof. Ariel Anbar
Arizona State University, Tempe, AZ, USA
Dr. Victor Balagansky
Geological Institute, Apatity, Russia
Prof. Mark Barley
University of Western Australia, Crawley, Australia
Prof. Jochen Brocks
The Australian National University, Canberra, Australia
Prof. Louis Derry
Cornell University, Ithaca, NY, USA
Prof. Anton Eisenhauer
GEOMAR, Kiel, Germany
Prof. Anthony E. Fallick
Scottish Universities Environmental Research Centre, East Kilbride, Scotland, UK
Prof. David Fike
Washington University, St. Louis, USA
Prof. Karl Föllmi
University of Lausanne, Lausanne, Switzerland
Prof. Robert Frei
University of Copenhagen, Copenhagen, Denmark
Dr. Dieter Garbe-Schönberg
Christian-Albrechts-Universität, Kiel, Germany
Prof. Eero Hanski
University of Oulu, Oulu, Finland
Prof. Raimo Lahtinen
Geological Survey of Finland, Espoo, Finland
Prof. Michail Mints
Geological Institute, Moscow, Russia
Prof. David Mossman
Mount Allison University, Sackville, NB, Canada
Prof. Richard Ojakangas
University of Minnesota, Duluth, USA
Prof. John Parnell
University of Aberdeen, Aberdeen, Scotland, UK
Prof. Adina Paytan
University of California, Santa Cruz, USA
Dr. Bernhard Peucker-Ehrenbrink
Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Prof. Igor Puchtel
University of Maryland, College Park, MD, USA
Prof. Robert Raiswell
University of Leeds, Leeds, UK
Prof. Robert Riding
University of Tennessee, USA/
Cardiff University, Wales, UK
Dr. Nathaniel Sheldon
University of Michigan, Ann Arbor, MI, USA
Dr. Graham Shields-Zhou
University College, London, UK
Dr. Craig Storey
University of Portsmouth, Portsmouth, UK
Prof. Kari Strand
Thule Institute, University of Oulu, Oulu, Finland
Prof. Frances Westall
Centre de Biophysique Moléculaire, CNRS, Orléans, France

Acknowledgements

The idea of making an atlas with comprehensive descriptions and illustrations of the Palaeoproterozoic rocks from the Fennoscandian Shield was initiated in 2009 during a workshop held in Trondheim, Norway, under the auspices of the International Continental Scientific Drilling Program (ICDP). Starting from this workshop, a plan was developed and finalised. Chris Bendall, Senior Editor for Springer, is acknowledged for encouragement and editorial supervision of the project.

The three-volume set has three major underpinnings. The first is many years of research in Precambrian geology of the Fennoscandian Shield by many workers, and we acknowledge particularly the support of the Geological Survey of Norway; the University of Oulu, Finland; and the Institute of Geology, Petrozavodsk, Russia.

The second is the unique core material obtained during the drilling operations by the Fennoscandian Arctic Russia – Drilling Early Earth Project (FAR-DEEP). The drilling operations were largely supported by the ICDP and by additional funding from several other agencies and institutions. We are grateful for the financial support to the Norwegian Research Council (NFR), the German Research Council (DFG), the National Science Foundation (NSF), the NASA Astrobiology Institutes, the Geological Survey of Norway (NGU) and the Centre of Excellence in Geobiology, the University of Bergen, Norway. The core archive and associated analytical work were supported by NGU, the Scottish Universities Environmental Research Centre (SUERC) and by the Pennsylvanian State University.

The third is a multidisciplinary approach to investigate complicated geological processes. This was provided by the international scientific community and we acknowledge the support of many universities in Scandinavia, Europe and the USA.

Many individuals helped in the preparation of the drilling operations and offered logistical support. We are sincerely grateful to Anatoly Borisov (Kola Geological Information and Laboratory Centre) for providing geological assistance for precise positioning of drillholes in unexposed, boggy and forested terrains in the Imandra/Varzuga Greenstone Belt. Stanislav Sokolov (Kola Mining Metallurgical Company) is acknowledged for logistic support and geological guidance in the Pechenga Greenstone Belt. Logistical organisation of the drilling operations and core transport across national borders by the State Company Mineral, St. Petersburg, Russia, is appreciated. The Finnish company, SMOY, performed the drilling.

Many organisations and people have provided rock samples, photographs, SEM images and permission to use figures. Thanks are due to the Geological Museum of the Department of Geosciences, University of Oulu; Geological Museum of the Geological Institute, Kola Science Centre, Apatity; Geological Survey of Finland; and to the following people: Wlady Altermann, Lawrence Aspler, Alex Brasier, Ronald Conze, Alenka Črne, Kathleen Grey, Jens Gutzmer, Eero Hanski, Emmanuelle Javaux, Yrjö Kähkönen, Vadim Kamenetsky, Reino Kesola, Andrew Knoll, Kauko Laajoki, Reijo Lampela, Aivo Lepland, Kevin Lepot, Zhen-Yu Luo, Vladimir Makarikhin, Tuomo Manninen, Jukka Marmo, Nicola McLoughlin, Pavel Medvedev, Victor Melezhik, Satu Mertanen, Tapani Mutanen, Lutz Nasdala, Richard W. Ojakangas, Domenic Papineau, Petri Peltonen, Vesa Perttunen, Vladimir Pozhilenko, Anthony Prave, Igor Puchtel, Jorma Räsänen, Pentti Rastas, Raimo Ristimäki, Alexander Romashkin, Dmitry Rychanchik, Ronny Schoenberg, Evgeny Sharkov, Igor Sokolov, Hubert Staudigel, Kari Strand, Sergey Svetov, Vladimir Voloshin, Frances Westall, Grant Young, Valery Zlobin and Bouke Zwaan.

Unpublished geochemical data were kindly provided by the Geological Survey of Finland, Zhorzh Fedotov, Valery Smol'kin and Peter Skuf'in. Permission to use published material was kindly given by the Royal Society of Edinburgh, Elsevier, John Wiley and Sons and Blackwell Publishing Ltd.

The book preparation was supported by the NFR (grant 191530/V30 to Victor Melezhik), Natural Environment Research Council (grant NE/G00398X/1 to Anthony Fallick, Anthony Prave and Daniel Condon), DFG (grants Str281/29, 32, 35 to Harald Strauss), NASA (grant NNA09DA76A to Lee Kump), NSF (grant EAR 0704984 to Lee Kump) and the Academy of Finland (grant 116845 to Eero Hanski).

To be embedded in the family of science always requires sacrifices such as time lost in family contact. We wish to extend our gratitude to our families for patience, understanding and constant encouragement.

Finally and most importantly, the editors wish to thank those colleagues and students who will use and read these books or some parts of them. We hope that this will encourage them to reach a more complete understanding of those processes that played an important role in the irreversible modification of Earth's surface environments and in shaping the face of our emerging aerobic planet. We would also like to thank those scientists who will use the offered advantage of rich illustrative material linked to the core collection to undertake new research projects.

Preface to Volume 1

Earth's present-day environments are the outcome of a 4.5-billion-year period of evolution reflecting the interaction of global-scale geological and biological processes. Punctuating that evolution were several extraordinary events and episodes that perturbed the entire Earth system and led to the creation of new environmental conditions, sometimes even to fundamental changes in how planet Earth operated. One of the earliest and arguably the greatest of these events was a substantial increase (orders of magnitude) in the atmospheric oxygen abundance, sometimes referred to as the Great Oxidation Event. Given our present knowledge, this oxygenation of the terrestrial atmosphere and the surface ocean, during the Palaeoproterozoic Era between 2.4 and 2.0 billion years ago, irreversibly changed the course of Earth's evolution. Understanding why and how it happened and what its consequences were are among the most challenging problems in Earth sciences.

The three-volume treatise entitled "Reading the Archive of Earth's Oxygenation" (1) provides a comprehensive review of the Palaeoproterozoic Eon with an emphasis on the Fennoscandian Shield geology; (2) serves as an initial report of the preliminary analysis of one of the finest lithological and geochemical archives of early Palaeoproterozoic Earth history, created under the auspices of the International Continental Scientific Drilling Programme (ICDP); (3) synthesises the current state of our understanding of aspects of early Palaeoproterozoic events coincident with and likely related to Earth's progressive oxygenation with an emphasis on still-unresolved problems that are ripe for and to be addressed by future research. Combining this information in three coherent volumes offers an unprecedented cohesive and comprehensive elucidation of the Great Oxidation Event and related global upheavals that eventually led to the emergence of the modern aerobic Earth System.

The format of these books centres on high-quality photo-documentation of Fennoscandian Arctic Russia – Drilling Early Earth Project (FAR-DEEP) cores and natural exposures of the Palaeoproterozoic rocks of the Fennoscandian Shield. The photos are linked to geochemical data sets, summary figures and maps, and time-slice reconstructions of basinal and palaeoenvironmental settings that document the response of the Earth system to the Great Oxidation Event. The emphasis on a thorough, well-illustrated characterisation of rocks reflects the importance of sedimentary and volcanic structures that form a basis for interpreting ancient depositional environments, and chemical, physical and biological processes operating on Earth's surface. Most of the structural features are sufficiently complex as to challenge the description by other than a visual representation, and high-quality photographs are themselves a primary resource for presenting essential information. Although nothing can replace the wealth of information that a geologist can obtain from examining an outcrop first hand, the utility of photographs offers the next best source of data for assessing and evaluating palaeoenvironmental reconstructions. This three-volume treatise will, thus, act as an information source and guide to other researchers and help them identify and interpret such features elsewhere, and will serve as an illustrated guidebook to the Precambrian for geology students.

Finally, the three-volume treatise provides a link to the FAR-DEEP core collection archived at the Geological Survey of Norway. These drillcores are a unique resource that can be used to help solve the outstanding problems in understanding the causes and consequences of the multiple processes associated with the progressive oxygenation of terrestrial environments. It is anticipated that the well-archived core will provide the geological foundation for future research aimed at testing and generating new ideas about the Palaeoproterozoic Earth. The three-volume treatise will be of interest to researchers involved directly in studying this hallmark period in Earth history, as well as professionals and students interested in Earth System evolution in general.

Volume 1: "The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia – Drilling Earth Project" describes the implementation of the FAR-DEEP drilling project in Arctic Russia. It summarises the knowledge of more than 50 years of largely Russian-led fieldwork, information hitherto virtually unavailable in the West, and provides geological description of drilling areas with an exhaustive illustration of rocks by high-quality, representative photographs. The volume offers a comprehensive review and rich photo-illustration of palaeotectonic, palaeogeographic and magmatic evolution of the Fennoscandian Shield in the early Palaeoproterozoic and links the evolution of the shield to the emergence of an aerobic Earth system. The volume unfolds the event-based Fennoscandian chronostratigraphy and discusses the chronology of the Palaeoproterozoic global events as the basis for a new subdivision of Palaeoproterozoic time.

Welcome to the illustrative journey through one of the most exciting periods of planet Earth!

Contents to Volume 1

Contents to Volume 2

Contents to Volume 3

Part I

Palaeoproterozoic Earth

1.1 Tectonic Evolution and Major Global Earth-Surface Palaeoenvironmental Events in the Palaeoproterozoic

V.A. Melezhik, L.R. Kump, E.J. Hanski, A.E. Fallick, and A.R. Prave

Many, if not all, of the long-term fluctuations in geological processes operating on Earth's surface are tectonically driven and related to the interplay of plate tectonics and deep mantle dynamics resulting in supercontinental cycles and (super) plume events (Condie et al. 2001; Condie 2004). These processes include the amalgamation, dispersal, collision and geographic position of major land-masses which dictate volcanic and hydrothermal activities, changes in sea level and the global patterns of ocean circulation, thermal isolation of continents, climate change, rate of continental weathering and its influence on seawater composition, and atmospheric oxygen budget via control of burial and recycling of carbon and sulphur. Further, all of these are reflected in biological processes. However, well-documented and well-constrained examples of this conceptual model have been developed and tested largely on Phanerozoic rocks (Valentine and Moores 1970; Fischer 1984; Marshall et al. 1988; Hardebeck and Anderson 1996; Berner 2006; Rampino 2010). Although there have been a number of attempts to apply such concepts to "Deep Time", in particular, the Palaeoproterozoic (Nance et al. 1986; Windley 1993; Lindsay and Brasier 2002; Condie et al. 2009), testing and verification of the models is challenging. The existence of continental masses, their palaeogeography and sizes in the late Archaean-early Palaeoproterozoic remain hypothetical and robust plate reconstructions are hampered by the small number of reliable palaeomagnetic data (Evans and Pisarevsky 2008).

In this review we will focus on those global environmental events that can be documented by physical evidence (i.e. features preserved in rocks) or well-established geochemical proxies (e.g. S and C isotope systems). Hence, this is not a comprehensive review of tectonically driven processes operating on Earth's surface during the Palaeoproterozoic; such details can be found in Reddy and Evans (2009). We limit this overview to the time interval, which closely preceded, was associated with, and postdated the emergence of an aerobic Earth system between 2.5 and 2.0 Ga (e.g. Melezhik et al. 2005a). We will focus on the series of environmental upheavals whose understanding has great potential to address a key question: what caused the irreversible oxygenation of the terrestrial atmosphere (the answers to which currently remain highly uncertain; Kump 2008)?

V.A. Melezhik (✉)
Geological Survey of Norway, Postboks 6315 Sluppen, NO-7491 Trondheim, Norway

Centre for Geobiology, University of Bergen, Allegaten 41, N-5007 Bergen, Norway
e-mail: victor.melezhik@ngu.no

1.1.1 Late Archaean Tectonic Restructuring

The pattern of radiometric ages for Palaeoproterozoic rocks exhibits two prominent peaks at 2.7–2.6 and 1.9–1.8 Ga (Gastil 1960; Worsley et al. 1984; Nance et al. 1986, 1988; Condie 1995, 1998, 2000; Campbell and Allen 2008; Condie et al. 2009). Both episodes are seen best in North America (Hoffman 1988, 1989) and have also been documented in the Fennoscandian Shield (e.g. Hanski et al. 2001; Nironen 2005; Lahtinen et al. 2005), though the main Archaean crustal growth episode seems to have occurred slightly earlier, at c. 2.8 Ga (e.g. Bibikova et al. 2005; Käpyaho et al. 2006; Mikkola et al. 2011). The major global growth peak of juvenile crust at 2.7 Ga has been suggested to be linked with a catastrophic mantle overturn event in a transitional period when mantle dynamics changed between layered mantle convection to whole-mantle convection favouring modern-day plate tectonic processes (Arndt 2004; Nelson 2004).

Palaeogeography

Archaean palaeotectonic reconstructions are still in their infancy (Sorjonen-Ward and Luukkonen 2005). Bleeker (2003) suggested that the global Archaean record includes c. 35 large cratonic fragments and several smaller slivers.

V.A. Melezhik et al. (eds.), *Reading the Archive of Earth's Oxygenation*, Volume 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia - Drilling Early Earth Project,
DOI 10.1007/978-3-642-29682-6_1, © Springer-Verlag Berlin Heidelberg 2013

Three very different late Archaean global plate reconstructions have been proposed based on palaeomagnetic data with acknowledged limitations (Mertanen and Pesonen 2005; Buchan et al. 2000; Halls et al. 2008; Evans and Pisarevsky 2008). Bleeker (2003) proposed two: one reconstruction includes all the cratons as a single supercraton named Kenorland, while the other proposes three separate supercontinents termed Vaalbara, Superia and Slavia, distinguished by slightly different cratonisation ages of 2.9, 2.7, and 2.6 Ga, respectively. The third of these reconstructions suggests the existence of two supercontinents, "Kenorland" and "Zimvaalbara" (for detailed discussion, see Reddy and Evans 2009). Kenorland includes the Laurentian, Fennoscandian and Siberian shields, whereas Zimvaalbara arguably comprises Zimbabwe, Kaapval, Pilbara, and perhaps the São Francisco and Indian cratons (Williams et al. 1991; Aspler and Chiarenzelli 1998).

Regardless of the exact number of supercontinents, geological evidence indicates that the late Archaean – early Palaeoproterozoic was a time of protracted break-ups, driven by inferred mantle plumes and associated intraplate rifting. Break-up of Zimvaalbara started at 2.65 Ga, Kenorland at 2.45 Ga and the final fragmentation of these supercontinents was during the 2.42–2.0 Ga time interval (Aspler and Chiarenzelli 1998). The initial break-up of Kenorland started at a low palaeolatitude (0–20 °; Christie et al. 1975) and was associated with the formation of a large continental flood basalt province including giant radiating dyke swarms and layered gabbro intrusions (Heaman 1997; Vogel et al. 1998). Attenuation of Zimvaalbara involved crust- and mantle-driven mafic magmatism at 2.47–2.43 Ma (Jones et al. 1975; Hamilton 1977) followed by rifting. In Australia, a 2.45 Ga mantle plume was also emplaced equatorially (05 °; Evans 2003), generating a large igneous province. Vast deposition of the 2.48–2.46 Ga banded iron formations in fringing seas, (Figs. 1.1 and 1.2a) coeval with initial rifting in Kaapvaal and Pilbara (Barley et al. 1997; Nelson et al. 1999; Martin et al. 1998; Pickard 2003) differentiates Zimvaalbara Paleoproterozoic events from those of Kenorland. This difference has been ascribed to contrasting palaeotectonic settings involving convergent (Kenorland) and rifted (Kaapvaal and Pilbara) margins of the large late Archaean cratons (Barley et al. 2005). In contrast, the latest significant BIF deposition in Kenorland (Fig. 1.2b) is dated at c. 2750 Ma (e.g. Bibikova 1989).

1.1.2 Newly Born Supercontinent(s) Through 2.4–c. 2.3 Ga Time Interval

Despite apparent differences in various palaeogeographic reconstructions, major cratons share several common features through the Archaean-Palaeoproterozoic transition: low-latitudinal and high-standing position, mantle plume generated gabbro plutons (Fig. 1.2c, d) and intraplate rifting, formation of large igneous provinces and widespread magmatic shut- or slowdown. These features were apparently palaeotectonic and palaeogeographic requirements for a series of unprecedented palaeoenvironmental upheavals that began around 2.4 Ga.

Global Magmatic Shut- or Slow-Down

The global distribution of U-Pb ages of subduction-associated granitoids and ages of detrital zircons suggest a widespread reduction in terrestrial magmatic activity and a significant lull in volcanism and crustal production during the c. 2.45–2.2 Ga time interval (Condie et al. 2009). It is also suggested that this was the period when the global subduction system shutdown since most terrestrial volcanism is related to plate tectonics. The mechanisms by which the global subduction system could completely shutdown were advanced by O'Neil et al. (2007) and Silver and Behn (2008).

Condie et al. (2009) provided a plausible causative link between magmatic stagnation and several global events. It is suggested that a drastic decrease of Fe^{2+} delivery to the oceans via submarine volcanism could shut down deposition of banded iron formations. This, combined with a drop in the rate of CO_2 venting from the mantle, could reduce the sink for oxygen thus leading to a cooler, more oxidising atmosphere capable of supporting global glaciation. It is important to point out that such a link offers a complementary "geotectonic" component, seemingly missing from the widely accepted explanations in which major modifications related to atmospheric composition and climatic changes are driven either geochemically or biogeochemically (Pavlov et al. 2000; Kasting 2004, 2005; Kopp et al. 2005).

Condie et al. (2009) also emphasise that the shutdown of the global subduction system should cool oceanic lithosphere, which would decrease ocean ridge volume, thus leading to deeper oceanic basins and a lower sea level (Moucha et al. 2008). Inevitable results include extensive and deep erosion of continental shelves, widespread unconformities, and the incompleteness of craton-margin sedimentary successions spanning the 2.45–2.2 Ga time-interval. This, combined with the scarcity of magmatic rocks suitable for dating, hampers the chronological reconstruction of events and the causative relationships between various factors operating during this enigmatic part of Earth's history.

Precise dating of sedimentation, perhaps by the Re-Os technique, and tracking of continental erosion rate by $^{87}Sr/^{86}Sr$ ratio in marine carbonates, represent major, and challenging, components of future research. Interestingly, the

Fennoscandian Shield is marked by an intensive intermediate-mafic volcanism dated at 2.43 Ga, and perhaps even younger (see Chaps. 3.2, 3.3, and 3.4), thus covering at least part of the period otherwise marked by stagnant magmatic activity. Sedimentary formations of the same age contain marine carbonate rocks that could be targeted for chemostratigraphy.

Global Glaciation and Oxygenation of Atmosphere

Radical modification of the Earth's surface environments may have started with the seemingly rapid onset of wide-spread glaciation (Fig. 1.2e, f; Young 1970; Visser 1971; Miall 1983; Marmo and Ojakangas 1984; Martin 1999; Young et al. 2001) from otherwise climatically stable conditions in the early Palaeoproterozoic (for details see Chap. 7.2).

With a partial overlap in time, this wide-spread glaciation was accompanied by the disappearance of mass-independent fractionation of sulphur isotopes (MIF-S) (Guo et al. 2009; for details see Chap. 7.1), a significant rise in atmospheric oxygen concentration (the "Great Oxidation Event"; Holland 2006), and the onset of a short-term global (however, for opposite view see Frauenstein et al. 2009), positive $\delta^{13}C$ anomaly in sedimentary carbonates reported from the Duitschland Formation in the Transvaal Supergroup of South Africa (Bekker et al. 2001). The MIF-S disappearance occurs between the first and the second (out of two) glacial units and can be constrained between 2.48 and 2.32 Ga (Hannah et al. 2004). A somewhat similar pattern is reported by Papineau et al. (2007) from within the Huronian Supergroup, Ontario, Canada, where the MIF-S signal was lost after the second (out of three) glacial unit. Similar to the Transvaal Supergroup, radiometric age constraint for the onset of the glaciation and the disappearance of MIF-S remains imprecise (between 2.45 and 2.3–2.2 Ga), as does the onset of an oxidising atmosphere.

Hence, it is evident that the Palaeoproterozoic started with several extraordinary events associated with radical changes in Earth surface environments and composition of the atmosphere. The question remains: what were the driving forces for such rapid and unprecedented modification of Earth surface conditions after several hundreds of million years of relative stability?

Several hypotheses advanced for explanation of these early Palaeoproterozoic events invoke the onset of oxygenic bacterial photosynthesis and the collapse of a methane-rich atmosphere; however, all suggested hypotheses have conflicting cause-and-effect relationships (Pavlov and Kasting 2002; Kopp et al. 2005; Zahnle et al. 2006; Konhauser et al. 2009). But, did the tectonically-driven palaeogeographic restructuring of major land masses and related changes in magmatic and metamorphic systems play any role in the geochemical and climatic modification of the Earth system (Catling and Claire 2005; Kump and Barley 2007; Condie et al. 2009)?

With tectonics as the major factor in mind, Barley et al. (2005) addressed the cause-and-effect relationships between tectonics and early Palaeoproterozoic environmental changes. Mantle plume breakouts were suggested as factors limiting ocean productivity, the rate of photosynthesis, and maintaining chemically reduced conditions throughout the Archaean. They also proposed that the establishment of large, thick and stable continental land masses (i.e. supercontinents, e.g. Kenorland) and a change in the style of plate tectonics at c. 2.4 Ga led to an increase in ocean productivity and photosynthesis rates. This, complemented by a decreased influx of chemically reduced gases produced by subaerial volcanism (Kump and Barley 2007), resulted in a reduced oxygen sink, the removal of methane greenhouse conditions and the build-up of an oxic atmosphere. The approach is definitely attractive and worthy of development; however, the resultant outcome appears to be convoluted due, mainly, to the incomplete geological record and poorly understood history of Palaeoproterozoic supercontinents and supercratons (Reddy and Evans 2009).

The most crucial factor hampering our understanding of the chronological sequence of events and their causative relationships during the 2.4–2.3 Ga time interval is the limited number of precise radiometric ages that may constrain onsets of different processes operating on Earth at that time. This concerns the important question: which of the three glacial episodes recorded in Canada correlate with the two reported in Africa and one known in Scandinavia? Which were global in nature? The incompleteness of the geological record, combined with a limited number of well-studied sections, causes a serious bias in geological and geochemical interpretations.

The disappearance of MIF-S is recorded in only two sections (in S. Africa and Canada) and so far cannot provide robust information on internal structure of such process. Was it an abrupt, single, irreversible process? Or perhaps it was marked by several reversals that signify a transitional period from anoxic to oxic conditions. Moreover, there is a high potential that some basal Palaeoproterozoic beds can still contain older detrital sulphides retaining MIF-S. This seems to be the case for some sulphides associated with the first glacial deposits above the BIFs in the Hamersley Group. They carry an MIF-S signal, however, the dating by a Re-Os technique shows that they are significantly older than the inferred age of the glaciations; a significant amount of sulphides in Archaean shales in Western Australia also have older detrital sulphides (Barley, personal communication). Consequently Re-Os dating of sulphides should be employed more widely in the study of sulphur isotopes during the Archaean-Palaeoproterozoic transitional time. This will help to confirm when the MIF stopped and how long it took for oxidative weathering to be established and stop older detrital sulphides retaining MIF-S being eroded, transported and deposited in younger sediments. This should also assist in unraveling the cause and effect of tectonics and the early Palaeoproterozoic environmental upheavals which continues to be a challenge.

1.1.3 Rifted Supercontinent(s) Through c. 2.3–2.1 Ga

The world database on igneous radiometric ages, including those from the Fennoscandian Shield (Hanski et al. 2001), suggests a rather stable tectonic regime with minimal or no collisional/accretional processes throughout the c. 2.4 to 2.2 Ga period (Condie et al. 2009). The response to this prolonged phase of high-standing, stable continents was the apparent formation of deeply weathered surfaces (e.g. Marmo 1992) and widespread unconformities (Condie et al. 2009; also see Chap. 7.9.2). Intraplate rifting resumed at c. 2.2 Ga and resulted in erosion of the deeply weathered rocks (Fig. 1.2g) and deposition of chemically mature arenites (Fig. 1.2h). This was accompanied by carbonate sedimentation in coeval, wide-spread, shallow-water platforms and epeiric seas.

Formation of Giant Manganese Deposits and World-Wide "Red Beds"

The depositional age of the Hotazel Formation containing a giant Mn deposit (Figs. 1.1 and 1.2i–j) remains poorly constrained between 2.4 and 2.2 Ga but very likely close to 2.4–2.3 Ga as, the banded iron formation rests immediately on Makganyene glacial beds. Manganese-rich strata of the Hotazel Formation in South Africa contain c. four billion tons of Mn within the Kalahari manganese field; this is by far the world's largest land-based Mn deposit (Gutzmer et al. 1997). Mn silicate (braunite) finely intergrown with Mn-rich carbonates (kutnahorite) form thick units within the magnetite-haematite type of banded iron formation, all of which record deposition on continental shelfs (Klein et al. 1987).

Deposition of the Kalahari manganese field represents a unique oxidation and Mn extraction event in the world oceans. Deposition requires large quantities of O_2, thus suggesting that the oxygenic photosynthetic apparatus (photosystem II) must have evolved before the formation of the Kalahari manganese deposit (Kirschvink et al. 2000). The oxidation and Mn extraction from seawater is also documented in the Fennoscandian Shield, though at a more modest scale (Fig. 1.2k).

In the Fennoscandian Shield, thin beds of manganite-cemented arenites occur within a shallow-water shelf dolostone-siliciclastic succession of the Tri-Ostrova Formation in the Ust'Ponoj Greenstone Belt (Melezhik and Predovsky 1984). Here, the manganite deposits are associated with ^{13}C-rich carbonate rocks of the Lomagundi-Jatuli type (Melezhik and Fallick 1996), hence represent a later and much more modest occurrence.

The post-2.2 Ga period was the time when Palaeoproterozoic "red beds" (rocks stained red by iron oxide, Fig. 1.2l) became widespread (Fig. 1.1). Red beds, together with lithified ancient sols that accumulated iron during weathering, reflect the presence of oxygen in subaerial environments.

One of the Greatest Perturbations of the Global Carbon Cycle: The Lomagundi-Jatuli Isotopic Event

Approximately contemporaneous with the world-wide appearance of red beds and formation of manganese deposits is the first global record of sedimentary carbonates unusually enriched in ^{13}C. Although accumulated in a variety of depositional settings, the ^{13}C-rich carbonate rocks appear to be mainly shallow-water, red coloured stromatolitic dolostones with abundant evaporitic features (Fig. 1.2h, m–o; reviewed in Melezhik et al. 1999a). This unprecedented perturbation of the carbon cycle was first recognised globally by Baker and Fallick (1989a, b), and is known as the Lomagundi-Jatuli isotopic excursion (e.g. Melezhik et al. 2005a). The event apparently lasted over 140 million years, and its duration was best constrained on the Fennoscandian Shield (Karhu and Holland 1996; Karhu 2005; Melezhik et al. 2007; Martin et al. 2010).

The causes and internal structure of this long-lasting isotopic perturbation of the global carbon cycle, as well as its exact chronological relationship with other roughly coeval global environmental changes, remain a matter of continuous debate. Several conflicting models have been advanced to explain the Lomagundi-Jatuli isotopic event starting with enhanced burial of organic carbon (Bakker and Fallick 1989a, b; Karhu and Holland 1996), methane cycling (Yudovich et al. 1991; Hayes and Waldbauer 2006), and a redox-stratified ocean (Aharon 2005; Bekker et al. 2008).

Melezhik et al. (1999a, 2005b) and Frauenstein et al. (2009) have argued that there has been considerable basinal modification (amplification) of the global $\delta^{13}C$ excursion, giving the impression that the global carbon cycle perturbation was much larger than it actually was. It also remains unresolved what role tectonics/plate-tectonics played in the onset, maintenance for over 140 million years, and the demise of the unprecedented global carbon cycle perturbation. It is evident that the excursion was preceded by the c. 2.4–2.2 Ga magmatic shutdown (Condie et al. 2009), and the major part of the isotopic event coincided with the palaeogeography of high-standing rifted continents, extensive chemical weathering, development of shallow-water carbonate platforms and epeiric seas, and flourishing stromatolite-forming cyanobacteria (e.g. Melezhik et al. 1999a).

The termination is contemporaneous with the final break-up of the Kenorland supercontinent and formation of deep-water siliciclastic seas (Bekker and Eriksson 2003; Bekker et al. 2003; Wanke and Melezhik 2005). Other details on the Lomagundi-Jatuli isotopic event are presented in Chap. 7.3; however, determining the global timing and regional influences for one of the most profound carbon isotopic excursions in Earth's history represent major challenges for future research.

Upper Mantle Oxidising Event

Towards the end of the Lomagundi-Jatuli event, a vast volume of highly oxidised lavas (Fig. 1.2p) was extruded across the Fennoscandian Shield (Chaps. 3.4 and 7.4). The eruption has been precisely dated at 2.06 Ga in the Pechenga and Imandra/Varzuga greenstone belts (Melezhik et al. 2007; Martin et al. 2010). These lavas form units up to 2 km in thickness in several greenstone belts, over an area of 5,000 km^2. If this considerable volume of lavas of large regional extent is not the result of surface oxidation, then they may represent the preserved remnants of high fO_2 eruptions, and reflect original upper mantle conditions modified through Archaean subduction of highly oxidised, oceanic slabs. These rocks are apparently too young to be a "smoking gun" for mantle redox evolution and the major cause for the Great Oxidation Event. Nevertheless they highlight the heterogeneity of upper mantle redox state. The reduction in oxygen demand associated with the eruption of these 2.06 Ga high fO_2 lavas might still have played an important role in sustaining oxic surface conditions, including the final accumulation of oxygen in the atmosphere during the course of the Great Oxidation Event.

Radical Change of Seawater Sulphate Reservoir

Towards the end of the positive $\delta^{13}C$ isotopic excursion many continents record formation of Ca-sulphates, which occur as ubiquitous pseudomorphs in various marine sedimentary rocks (Fig. 1.2q–s; for details see Chap. 7.5). The sulphate-bearing strata formed in a variety of depositional settings ranging from lacustrine and marine intracratonic basins through passive margin and back-arc environments (El Tabakh et al. 1999; Melezhik et al. 2001, 2005b; Pope and Grotzinger 2003; Evans 2006; Schröder et al. 2008). Oceanic sulphate abundance remains unknown, but a sizeable sulphate reservoir suggested as early as 2.1–2.2 Ga (e.g. Melezhik et al. 2005b) would contrast with the view that, prior to the Mesoproterozoic, gypsum precipitation was inhibited by a small marine sulphate reservoir and higher marine carbonate saturation (Grotzinger 1989; Kah et al. 2004). The irregular, cyclic, secular variations of geochemical parameters known for Phanerozoic terrestrial hydrosphere and atmosphere systems (Budyko et al. 1985; Veizer 2005) should be, in principle, applicable to the Palaeoproterozoic and may provide a means for reconciling the two conflicting views. However, recently the small marine sulphate reservoir hypothesis has been challenged by the discovery of several tens of meters of massive anhydrite beds in the Onega Basin (Fig. 1.2t). The anhydrite strata are associated with the ^{13}C-rich dolostones of the Tulomozero Formation and represent the Lomagundi-Jatuli isotopic excursion, thus falling within the 2.22–2.06 Ga time-interval. This new discovery (Morozov et al. 2010) may cause us to rethink our interpretations of Palaeoproterozoic oceanic sulphate chemistry.

1.1.4 Dispersed Kenorland Supercontinent Through 2.1–1.9 Ga

Several hundred millions of years of tectonic stability punctuated with repeated intraplate rifting eventually resulted in supercontinent fragmentation at around 2.1–2.0 Ga. This is best documented in the Wyoming craton and Fennoscandian Shield (Bekker and Eriksson 2003; Daly et al. 2006; Lahtinen et al. 2005). How such a radical palaeogeographic reconfiguration and change in tectonic regime of this large land mass might have influenced weathering and burial cycles remains to be studied; however, one of the apparent consequences was the termination of the Lomagundi-Jatuli positive isotopic excursion of carbonate carbon, the greatest in Earth's history. Whether this was a coincidental or a causative relationship is the task for future research.

Enhanced Gglobal Accumulation of Organic Matter: The Shunga Event, and Giant Iron-Ore Deposits

The aftermath of the Lomagundi-Jatuli excursion was marked by another apparently global-scale event, an unprecedented accumulation of organic matter known as the Shunga Event (Figs. 1.1 and 1.2u; Melezhik et al. 1999b, 2004). Although documented on several continents, it is best represented in basins across the Fennoscandian Shield and in the Francevillian Series in Gabon (Chap. 7.6). The initial stage of "black shale" accumulation may partially overlap with the end of the Lomagundi-Jatuli excursion in Gabon (supplementary material in El Albani et al. 2010); this, though, is an exception and such shales are unlikely to be a coeval and complementary reduced carbon reservoir compensating for the 140 Ma-long Lomagundi-Jatuli positive isotopic excursion of $\delta^{13}C_{carb}$. Moreover, the continuous accumulation of vast volume of "black shales" in post-2.0 Ma time period, reaching several hundreds of meters in thickness, and containing up to 10–30 wt.% C, in numerous basins world-wide (Salop 1982; Melezhik et al. 1988; Condie et al. 2001), has not been reflected in isotopic composition of contemporaneous sedimentary carbonates (Karhu 1993; Melezhik et al. 2007).

The duration and the cause of enhanced accumulation of organic matter at c. 2.0 Ga have been only cursorily investigated and addressed in the published literature (e.g. Melezhik et al. 1999b; Mossman et al. 2005). Available radiometric dates from the Pechenga Greenstone Belt suggest that the event may have lasted less than 50 Ma (Hanski 1992; Melezhik et al. 2007).

This period of time is also known for the generation of supergiant oil deposits, perhaps for the first time in Earth's history in such volume and scale (Mossman et al. 2005; Melezhik et al. 2009). One of these petrified oil fields is preserved in the Onega Basin in the southeastern Fennoscandian Shield (Fig. 1.2v–x; for details see Chap. 7.6). This oil field possesses rich information with a great potential to elucidate petroleum generation and migration in the Palaeoproterozoic (Melezhik et al. 2009).

Why did the oldest known significant accumulation of organic-carbon-rich sediments and generation of large-scale petroleum deposits occur at around 2.0 Ga, if the fundamental features of the biologic carbon cycle were established by 3500 Ma (Schidlowski et al. 1975; Hayes et al. 1983; Grassineau et al. 2002)? Does this accumulation of organic-carbon-rich sediments reflect an episode of enhanced biological productivity in a nutrient-enriched ocean? Or, perhaps such 2.0 Ga occurrences were the result of biased preservation or are the result of modest productivity, but enhanced preservation or even a preservation bias? All these questions constitute a programme for investigating this fascinating period of the Palaeoproterozoic (Melezhik et al. 1999b; Papineau 2010).

The c. 2.1–1.9 Ga time interval is also characterised by formation of giant supergene iron-ore deposits. Recently obtained new precise Pb/Pb ages on baddeleyite provided 2.05–2.0 Ga constraint on ore genesis in the Hamersley province in Western Australia. Müller et al. (2005) demonstrated that hypogene iron-ore mineralisation (shortly postdating the emplacement of c. 2008 Ma dikes) was oxidised, reworked and enriched by supergene processes during c. 2.0 Ga uplift and continental rifting. Müller et al. (2005) also suggested that these rift-bound giant supergene iron-ores were coeval with another class of giant iron-oxide accumulations (i.e., iron oxide (rare earth element–Cu-Au-U) deposits, Barton and Johnson (1996)) occurring in a similar continental rift setting. They suggested further that several world-class iron-ore deposits in India, South Africa, Brazil, and Ukraine exhibit remarkably similar enrichment processes and relative timing relationships close to 2.0 Ga (Beukes et al. 2003; Dalstra et al. 2003; Müller et al. 2005). In Western Australia, similar to the Fennoscandian, Canadian shields and many other cratons, the period between 2.1 and 2.0 Ga was characterised by continental sedimentation and mafic magmatism in extensional settings within rift basins that were linked to the breakup of a Paleoproterozoic supercontinent (e.g. Aspler and Chiarenzelli 1998). Supercontinent breakup may have caused the accumulation of hypogene iron ores followed by their first exposure and supergene oxidation in rift basins worldwide Müller et al. (2005).

The Earliest Phosphorites: A Radical Change in the Phosphorous Cycle

The 2.0 Ga enhanced accumulation of organic matter also corresponds in time with the formation of the oldest phosphorites (reviewed in Papineau 2010; Fig. 1.1). The phosphate accumulations occur in different forms (Chap. 7.7). The most remarkable c. 2.0 Ga occurrence is the Jhamarkotra stromatolitic phosphorites (Fig. 1.2y) containing up to 35 wt.% P_2O_5 and reaching 25 m in thickness in the Lower Aravalli Group in Rajasthan, India (Banerjee 1971; Chauhan 1979). Similar age phosphorites, though in redeposited, clastic form (Fig. 1.2z), occur in the c. 2.0 Ga Pilgujärvi Sedimentary Formation of the Pechenga Greenstone Belt (Bekasova and Dudkin 1982). Concretions enriched in phosphorus (Fig. 1.2aa, ab) have been documented in the Il'mozero Sedimentary Formation in the Imandra/Varzuga Greenstone Belt (Melezhik 1992). Phosphorites occur also as discrete bands in a c. 2.0 Ga iron formation in the Central Lapland Greenstone Belt (Gehör 1994). Other phosphorite occurrences are summarised in (Chap. 7.7).

The appearance of phosphorites in various forms in sedimentary successions at 2.0 Ga reflects a critical change in the Precambrian phosphorous cycle. The most common pathway of precipitation involves sedimentation of organic matter that carries biologically concentrated phosphate (Knudsen and Gunter 2002). Most of the reported 2.0 Ga phosphorites are commonly associated with sulphides and organic matter, and thus are consistent with such a mechanism. However, high bioproductivity and enhanced concentration of organic matter (e.g. Papineau 2010) is probably not the only factor controlling the generation of Palaeoproterozoic phosphorites; several older C_{org}-rich formations are known (Hayes et al. 1983), but contain no phosphorites. Thus, it is possible that 2.0 Ga sediments record a major change in the diagenetic mineralisation of organic matter, which seemingly was coeval with accumulation of the first phosphorites. One of the possible factors preventing the diffusion of P out of the sediment could be the establishment of a ferric oxide "trap" at the sediment-water interface overlain by oxic water. Other factors, which controlled the formation of the oldest known phosphorites and phosphate concretions remain unresolved.

Establishment of an Aerobic Pathway in Recycling of Organic Matter

The scarcity of diagenetic carbonate concretions in the Archaean and in the early Palaeoproterozoic sedimentary formations older than c. 2.0 Ga was acknowledged long ago (e.g. Pettijohn 1940; Melezhik 1992), and is evident from a later extensive carbonate concretion bibliography listing 700 articles (Dietrich 1997). Importantly, a compilation of published global data shows that $\delta^{13}C$ values of both primary and diagenetic carbonates of pre-c. 2.0 Ga rocks mostly cluster near $0 \pm 3‰$, which are not characteristic of microbially recycled organic matter (Fallick et al. 2008). However, carbonates associated temporally and spatially with banded iron formations (BIF) represent an exception (summarised in Fallick et al. 2011).

The first known appearance, and then worldwide development, of microbially meditated, ^{13}C-depleted, diagenetic carbonate concretions outside a "BIF-environment" are documented in published literature at around 2.0 Ga (Winter and Knauth 1992; Melezhik et al. 1998, 1999b; Fallick et al. 2008). In c. post-2.0 Ga sedimentary successions, the concretions are varied and abundant (Fig. 1.2ac) and associated with other diagenetic products, such as phosphate nodules and redeposited bedded phosphorites, all of which are seemingly absent from older rocks. Thus, it appears that the first abundant occurrence of isotopically light diagenetic carbonate concretions signifies an important hallmark in biospheric evolution apparently linked to the emergence of 'modern-style' recycling of organic matter (Melezhik et al. 2005a). It has been suggested (Fallick et al. 2008) that prior to c. 2.0 Ga organic matter was recycled and remineralised predominantly in the anoxic water column and near the sediment/water interface allowing isotopically distinctive CO_2 and CH_4 to readily escape to the atmosphere, thus leaving no isotopic traces in diageneticaly formed carbonates. Fallick et al. (2008) also suggested that around 2.0 Ga, the water column became oxic enough to be toxic for the anaerobic microbial recyclers, forcing them to retreat deep into the substrate. As the result, redox gradients developed in the sedimentary column and abundant carbonate concretions formed incorporating ^{13}C-depleted by-products derived from remineralised organic carbon, similar to what is observed in the Phanerozoic world. This hypothesis represents another subject for future research and tests. Another question to be answered is why diagenetic carbonates with distinct isotopic fingerprints of methanogenesis and methanotrophy (e.g. ^{13}C-rich) have not been confidently recorded in the early Palaeoproterozoic sedimentary formations? Or, perhaps their absence is the result of biased sampling? Hayes (1994) documents organic matter in 2.7 Ga sedimentary rocks that they attributed to methanotrophy. If this were widespread, we would expect ^{13}C-rich diagenetic carbonates to have been preserved. Moreover, younger Neoarchaean rocks do not display such ^{13}-C depleted organic matter. Was this a false start of the aerobic biosphere (whether the oxidant used in methanotropy was sulphate or oxygen)? Detailed and systematic mineralogical, petrographic, geochemical and in situ isotopic studies of diagenetic carbonates of this age may provide the focus necessary to examine this problem.

1.1.5 Summary

A brief review of some of the major modifications of the Earth surface environments emphasises that the Archaean-Palaeoproterozoic transition was a major step towards emergence of an aerobic Earth system. What remains unresolved is precise absolute chronology of all these major events. At present, even a relative chronological sequence can only be established with a certain amount of approximation. This, together with the limited palaeomagnetic database and unreliable palaeogeographic reconstructions, hampers our understanding of causative effect of palaeotectonics and Earth's surface alterations, as well as the cause-and-effect relationships between various global environmental changes.

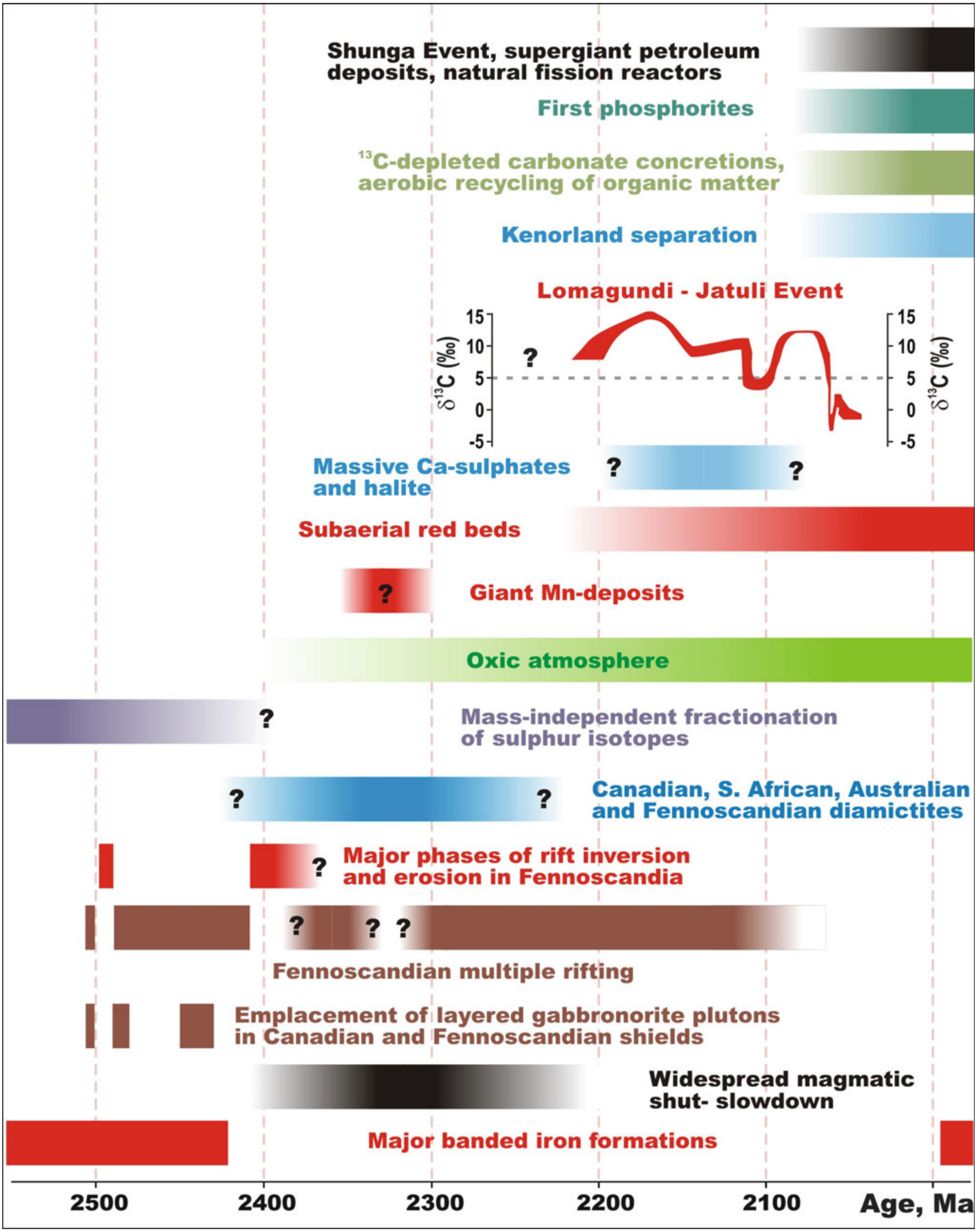

Fig. 1.1 Major global palaeoenvironmental and tectonic events during the Early Palaeoproterozoic (Data sources are presented in Chaps. 3.2, 3.3, 3.4, 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, and 7.7, and in Müller et al. (2005), Melezhik et al. (2007) and Condie et al. (2009))